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ADP013883

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ADP013843 thru ADP013888

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Vestibular Stimuli May Degrade Situation Awareness Even When Spatial Disorientation is not Experienced

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Summary

Spatial disorientation (SD) is an important contributor to aviation mishaps. Misleading acceleration stimuli during flight are one of the main causes of SD. SD is associated with a loss of situation awareness (LSA) and the commission of dangerous errors, yet little is known concerning the specific interactions among SD, LSA, and human error. While SD is likely to be an important contributor to LSA and human error, the interaction is complicated because acceleration stimuli to the vestibular organs degrade a person's well-being and performance even when spatial disorientation (SD) is not experienced. This paper points out theoretical gaps in knowledge concerning LSA, SD of vestibular origin, and vestibular effects other than SD. The authors argue for a wider consideration of the ways in which vestibular acceleration stimuli contribute to unsafe conditions for vehicle operators. While vestibular acceleration stimuli can elicit SD, they can also challenge psychomotor performance, visual performance, and certain aspects of cognition. A complete approach to the study of acceleration-induced human error and LSA should assess these various decrements in human functioning simultaneously, so the relative contribution of each decrement to the commission of error can be understood and the interactions among the decrements described.

Introduction to Spatial Disorientation (SD)

Modern vehicles and displays expose personnel to disorienting real or apparent accelerations. Real acceleration refers to physical acceleration of the human body, such as during flight maneuvers. Real acceleration can include sudden accelerations that are hazardous to one's skeleton and internal organs or sustained high-G maneuvers requiring special precautions to prevent G-induced loss of consciousness (GLoC). In this paper, the phrase "real acceleration" will denote acceleration stimuli that affect the vestibular and somesthetic receptors without directly producing body damage via mechanical shock or GloC via cardiovascular mechanisms. (Note, however, that vestibular effects complicate the view that GloC is purely a cardiovascular phenomenon, according to Cheung & Bateman, 2001).

The second category of acceleration stimuli mentioned in the last paragraph was "apparent acceleration." Apparent acceleration refers to visual, auditory, or somesthetic display conditions conducive of illusions of self motion or orientation, such as occur during exploration of a virtual environment or "flying" in a simulator. Although real acceleration is the focus of this paper, the vestibular system also responds to whole-field visual motion, which stimulates some of the same brain centers that process whole-body motion stimuli (Dichgans & Brandt, 1978). Moreover, since visually-

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

induced illusions of self motion (known as vection) can be produced during certain conditions of flight (Gillingham & Previc, 1996), apparent acceleration is not merely a simulator issue. While an episode of SD during exposure to a simulator or virtual environment would not be dangerous, the vestibular aftereffects of exposure to apparent acceleration are potentially hazardous (Stanney, ed., 2002), as are the effects of vection illusions during real flight (Gillingham & Previc, 1996).

There has been some controversy over how narrowly SD should be defined (Navathe & Singh, 1994; Previc, Yauch, DeVilbiss, Ercoline, & Sipes 1995; Cheung, 1995; Cheung, Money, & Sarkar, 1996), but in the aviation setting, a commonly used definition of SD is a failure by the aviator (or flight crew) "…to sense correctly the position, motion, or attitude of the aircraft or of him/herself within the fixed coordinate system provided by the surface of the earth and the gravitational vertical" (page 419, Benson, 1988). SD can be caused by illusions of body position, motion, or orientation whose origins lie in the visual, somesthetic, and vestibular modalities. Episodes of SD are often distinguished from geographic disorientation or "getting lost", due to a navigational error that affects an aviator's appreciation of his route, bearing, latitude, or longitude within fixed coordinates on the surface of the earth (Benson, 1988; United States Naval Flight Surgeon's Manual, 1991; Gillingham & Previc, 1996; Ercoline & Previc, 2001). Note that misjudgments of altitude are usually considered part of SD (Lyons, Ercoline, Freeman, & Gillignham, 1993; Previc, Yauch, DeVilbiss, Ercoline, & Sipes, 1995), because the operational characterization of SD includes a misperception or lack of awareness concerning the magnitude or direction of aircraft control and performance parameters, including altitude, attitude, and vertical velocity (Gillingham, 1992)

Estimates vary widely concerning the prevalence of SD-related mishaps (Lyons, Ercoline, Freeman, & Gillingham, 1994). For example, in U.S. rotary-wing operations, when estimates of SD-related mishaps are calculated as a percentage of total mishaps by service, estimates vary from 30% for the U.S. Army (Braithwaite, Durnford, Crowley, Rosado, & Albano, 1998) to 42% for U.S. Marine Corps (Mason, 1997). Gillingham (1992), Lyons et al. (1994) and Johnson (2000) believed that most published SD estimates were too conservative. Gillingham (1992) pointed out problems with mishap classification and conjectured that SD caused as many as 2-3 times more U.S. Air Force mishaps than the incidence statistics would lead us to believe. Johnson, (2000) stated that SD mishaps in the U.S. Navy may be twice as likely as the statistics would indicate, accounting for 26% of all the most serious (Class A) Mishaps (U. S. Naval Flight Surgeon's Manual, 1991) and claiming nearly three times more lives than non-SD mishaps. SD mishaps are often fatal, accounting for the loss of about 40 lives per year in the U.S. Air Force, Navy and Army combined (Braithwaite et al., 1998; McGrath, 2000).

Lyons et al. (1994) discussed several classification problems they observed in the mishap data, including failure to clarify the relationship of SD to mishaps that involved continuing VFR flight into adverse weather. Lyons et al. (1994) noted that a simple change in the accident reporting form increased the rate of categorization of accidents as SD-related. Whereas the old accident investigation form listed "visual illusions" and "disorientation/vertigo" as choices, the new form substituted the currently-accepted categories of SD as possible choices on the form. The three categories of SD listed on the form were type 1 (unrecognized), type 2 (recognized), and type 3 (incapacitating). The result of this change was an increase in choosing SD as a causal factor during low-level navigation, from 7% with the old form (FY86-FY89) to 67% with the new form (FY90-91). One of the key advantages of the newer form was that it listed "unrecognized SD." This change implicitly promoted the selection of SD as a mishap contributor in cases where the pilot did not report having suffered an acute and recognizable vestibular illusion, such as an attack of "the leans", but the accelerations the pilot experienced and the control inputs the pilot made indicated that the pilot was spatially disoriented (Benson, 1988).

The vestibular organs have been the focus of many past efforts to understand the SD aviators experience during flight. The vestibular organs are important because they constitute the key sensory modality specifically evolved to detect acceleration of the head in inertial space, yet they are not designed to provide veridical body orientation information within the unusual sensorimotor and force environments that occur during aerospace operations. Military aviators are familiar with the classic "vestibular" (or more accurately, vestibular/somesthetic/visual) spatial orientation illusions that are associated with SD during the physical accelerations occurring in flight. There are numerous, well-documented illusions that have a vestibular component, including the leans, the somatogravic/oculogravic illusions, the elevator illusion, the somatogyral/oculogyral illusions, the Coriolis cross-coupling illusion, the G-excess effect, the giant hand illusion, the inversion illusion, the visual vection illusion, and the Gillingham Illusion (Benson, 1988; U.S. Naval Flight Surgeon's Manual, Third edition, 1991; Gillingham & Previc, 1996; Cohen, 1973; Ercoline, Devilbiss, Yauch, & Brown, 2000). Similar illusions of perceived motion or posture are associated with the aftereffects of space flight (Nicogossian, Huntoon, & Pool, eds., 1989), simulator exposure (McCauley, ed, 1984), and virtual environment exposure (Stanney, ed., 2002).

One of the more common "vestibular" SD illusions in flight is "the leans" (Benson, 1988), which entails an erroneous feeling of roll orientation. A typical case occurs during recovery from a turn while flying without outside visual cues. Upon recovery from the turn, the aviator may feel banked when he or she is actually flying "wings level." (The vestibular mechanisms for this illusion are explained by Benson, 1988 and by Gillingham & Previc, 1996.) The fact that the leans and numerous other SD illusions have been named and explained does not imply the victim explicitly recognizes them during an episode of SD. In fact, SD usually occurs without being recognized (Braithwaite et al., 1998). One example of unrecognized SD (known as type 1 SD) occurs during mild acceleration of a helicopter. Hovering a helicopter is a demanding visual exercise requiring the aviator to use at least three visual reference points continually (one forward, one right and one left) to maintain the hover over a particular spot. In conditions of low visibility, it is difficult to find visual reference points and the aviator may begin to drift slowly in a linear fashion (right, left, forward or back). In such a situation, the acceleration stimulus might be below the threshold of vestibular and somesthetic detection and with visual cues degraded, the aviator will not appreciate the drift that is occurring. If the aviator does not attend to the flight instruments immediately, LSA will occur, the drift will go undetected and the helicopter might impact a nearby object. This sub-threshold acceleration event is clearly a case of SD in that it entails feeling one is not moving when one is. This example was chosen to illustrate three important points: 1) SD can occur without being recognized; 2) SD can occur without the presence of a strong acceleration stimulus; 3) An illusion with a vestibular component does not have to be categorizable as one of the classical "vestibular" SD illusions in order to qualify as an SD event. For further information on disorienting illusions with a vestibular component, the reader should refer to Lawson, Sides, and Hickinbotham (2002, ed. Stanney) and chapter 3.210, volume 1 of Boff and Lincoln, 1988.

Spatial Disorientation (SD) Versus Loss of Situation Awareness (LSA)

Situation Awareness is a more general concept than SD. In 1994, Dominguez counted 15 different definitions for SA, and the number has grown since then. However, Endsley's definition (1988, p. 97) is the one most commonly cited: "the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future." Thus, SA encompasses at least three concepts: perception (of cues), comprehension (of significance of cues), and projection (of future events). The concepts that characterize SA appear to be convergent with attention (Taylor, 1990), workload (Hendy, 1996; Vidulvich, Stratton, Crabtree, & Wilson, 1994), pattern recognition (Kass, Herschler, & Companion, 1991), mode error (Sarter & Woods, 1995), mental models (Mogford, 1997), platform-specific flight experience (Carretta & Ree, 1996), and certain aspects of memory (Sarter & Woods, 1991; Fracker, 1988). Selective attention is one of the constructs that should be especially convergent with SA, because selective attention is the preferential selection process that determines which environmental cues are perceived and comprehended (Endsley, 2000). The critical importance of attention to SA was supported by Taylor (1990), who empirically derived three cognitive dimensions of SA: 1) demand on attentional resources (related to instability, variability, and complexity of the situation), 2) supply of attentional resources (related to the human operator's state of arousal, spare mental capacity, concentration, and division of attention), and 3) understanding of the situation (related to quantity and quality of information received and understood and familiarity with the situation).

Initial attention to and perception of environmental cues appear to be important to understanding the relation between LSA and accidents. Endsley (1995) analyzed 24 major air carrier accidents reported by the National Transportation and Safety Board from 1989-1992. Endsley identified human error (excluding error during maintenance operations) as a contributing factor in 17 of the 24 accidents. She created several categories of contributory factors for human error: decision-making, SA, physiological, procedural, and psychomotor. The most common contributing factor was loss of SA, accounting for 15 (88%) of the 17 human error accidents. For the 15 accidents in which SA error occurred, a total of 32 SA errors were present, 23 of which (72%) involved level 1 SA errors, i.e., a failure to perceive the needed cues. However, many LSA accidents involved additional factors that contributed to the SA error. Four of the accidents involved some sort of physiological degradation, usually fatigue. Six accidents involved a violation of procedure, usually involving omitting a task. Four of the accidents involved bad decision-making, such as proceeding into inclement weather and neglecting to fly by instruments when needed, or continuing on what should have been called an aborted or missed approach. Two accidents involved psychomotor skills needed to control the aircraft.

Jones and Endsley (1996) analyzed 143 incidents reported in the database of the Aviation Safety Reporting System (1989-1992). They found that of 143 incidents reported, 111 (78%) involved SA errors on the part of the flight crew and 32 (22%) involved SA errors on the part of air traffic controllers. Endsley employed the aforementioned taxonomy containing three levels of SA: 1) perception of needed cues in the current situation, 2) comprehension of the current situation and the relevance of the cues to one's goals, 3) projection from current events to future status. The incidents summarized by Jones and Endsley (1996) included 262 different SA errors, 76% of which could be traced to type 1 LSA – a simple failure to perceive the needed information (or to perceive it correctly). Failure to perceive the needed information could be broken down further into 5 subcategories, as follows: a) data not available, b) hard to discriminate or detect data, d) failure to monitor or observe data, d) misperception (not due to sensory illusions, but to factors such as negative interference and confusing currently available information with the information sought), e) Memory Loss (forgetting of information previously in awareness). The most common reason for a type 1 SA failure (to perceive the needed cues) was found in subcategory c) – failure to monitor or observe available data, which comprised 35% of total SA errors. A failure to monitor or observe relevant data that is readily available can be attributed to a number of factors, among which momentary task distraction and high workload are the most important (23% of total SA errors).

Several inferences can be drawn from the accident and incident findings of Endsley (1995) and Jones and Endsley (1996). Firstly, the findings indicate that LSA does not often occur in isolation from other contributors, such as fatigue, errors of omission, or failing to switch to instrument flight when needed. Secondly, the findings imply that when LSA occurs, aviators are not usually losing SA due to a high-level failure of cognitive interpretation, comprehension, or prediction of events, but rather because of a simple failure to perceive or attend to needed data. Concerning the type of data that is missed, studies of aircraft mishaps indicate that failure to attend to data from the altitude indicator is crucial (Flight Safety Foundation, 1999). It is also likely that since aviators spend much of their scan time on the attitude indicator and the directional gyro (Simmons, Lees, & Kimbal, 1978), so information from these instruments may be especially affected by periods when one is attending to other displays or tasks.

A similar tendency not to recognize hazards during moments of distraction has been noted by SD researchers. The typical SD mishap occurs when visual attention is distracted from the aircraft's orientation instruments and the horizon is not visible or not being monitored (McGrath, 2000). The majority of SD mishaps are related to type 1 or unrecognized SD. Specifically, 100% of U.S. Air Force SD mishaps during 1990-91 were related to unrecognized SD (Lyons et al., 1993), while 90% of U.S. Army SD mishaps from 1987-1995 were related to unrecognized SD (Braithwaite, Groh, & Alvarez, 1997, Durnford, Crowley, & Rosado, 1995). In contrast, relatively few SD mishaps are attributed to SD that is recognized (type 2) or SD that is completely incapacitating (type 3).

Mishap findings from civil aviation correspond to the trends mentioned above. In civil aviation, one of the most frequent mishap categories is controlled flight into terrain (CFIT), wherein the crew flies a serviceable aircraft into the ground without being aware they are doing so, or with awareness coming too late. By the end of the 1980s, better training and technology had reduced the likelihood of midair collisions and wind-shear accidents dramatically, but the CFIT accident fatality category had grown to 81% of the total (Flight Safety Foundation, 1996). Among worldwide airlines from 1991 to 1995, there were more CFIT accidents than any other type (Flight Safety Foundation, 1996). According to a task force sponsored by the Flight Safety Foundation (1996), the International Civil Aviation Organization, and the U.S. Department of Transportation, there are two basic causes of CFIT accidents: "…the flight crew's lack of vertical position awareness or their lack of horizontal position awareness in relation to the ground, water, or obstacles. More than two-thirds of all CFIT accidents are the result of altitude error or lack of vertical situational awareness" (page 3.8, CFIT Education and Training Aid, Flight Safety Foundation, 1996).

Thus, the incident and mishap data from various settings suggest that SD mishaps, LSA incidents, and CFIT accidents frequently occur under similar conditions; namely, when there is a failure to perceive the position (or motion) of the aircraft correctly. Such outcomes usually occur under conditions of distraction with other flight tasks or high workload. However, while distraction and workload are very important accident contributors, they do not usually cause accidents in isolation from other factors. Rather, distraction becomes hazardous because one's attention is drawn away from cues concerning aircraft position while one's aircraft is flying close to the earth or other significant objects. In fact, the majority (60.9%, according to Figure 10 of the CFIT Education and Training Aid, Flight Safety Foundation, 1996) of all civil aviation accidents occur during the descent, approach, and landing phases of flight, when distraction and workload are higher and the margin for positional error is lower than during the cruise portion of flight (4.5%). Typically (Flight Safety Foundation, 1998, 1999), approach-and-landing accidents are classified as decision errors because the flight crew decided to descend below the minimum height for a "go around" decision, despite the absence of adequate outside visual cues. However, CFIT is explicitly recognized when it is obvious the flight crew lost accurate awareness of their position relative to the ground.

The authors believe that the inability of an aviator (or a flight crew) to accurately perceive aircraft position intuitively and without reliance upon visual cues (from flight instruments or the outside world) is a major crux of the aviation mishap problem. Gillingham (1992) pointed out that the majority of LSA mishaps in his database would not have happened if the pilots had not been spatially disoriented. Maintaining spatial orientation is a key prerequisite to maintaining situation awareness, but it cannot be done in present-day flight operations unless one is attending to the appropriate visual cues. Unfortunately, many of an aviator's distracting secondary flight tasks are also of a visual nature so continuous attention to one's spatial orientation cannot be maintained using current visual displays. The problem concerning the allocation of limited attentional resources is compounded by the fact that attentional resources will be drawn to more natural and salient body cues concerning orientation, which in the environment of flight are not veridical. In other words, the problem of LSA in flight is not caused merely be the formation of an incomplete mental model due to attentional limitations; rather, the problem is the formation of an incorrect, yet persuasive mental model due to one's subconscious tendency to rely upon vestibular and somesthetic orientation cues.

For these reasons, current flight displays offer ample opportunity for falling prey to distraction from primary flight cues. New instruments are under development that should help to decrease this problem by presenting visual information in fewer and more intuitive displays (Still & Temme, 2001). Also, investigations are underway to test the usefulness of providing continuous cutaneous cues for orientation (Raj, McGrath, Rochlis, Newman, & Rupert, 1998) and determine whether they are more resistant to distraction by competing visual tasks (Raj, Kass, & Perry, 2000).

Despite the likely importance of SD to LSA, the obvious overlap in these two concepts, and the similar pattern of mishap findings for SD and LSA investigations, little explicit overlap occurs in the literature concerning these two concepts or in the training that aviators receive. Much of the SD literature does not discuss the nature of the relationship between SD and LSA, although there are several notable exceptions (Benson, 1988; Gillingham, 1992; Cheung, Money, & Sarkar, 1996). The situation is no better in the SA literature, despite the fact that the SA literature describes a theoretical concept that appears to encompass SD (Benson, 1988). For example, a recent book on SA edited by Endsley & Garland (2000) is very informative about SA, but does not include index entries for any of the following terms: "orientation," "disorientation," "spatial orientation," "spatial disorientation," "vestibular," "acceleration," "motion," "position," "force," "G-force," "illusion," or "vertigo." The 383-page book contains indexes for four pages concerning "spatial abilities," but none of these pages is directly pertinent to spatial disorientation vis à vis the surface of the earth or the direction of Earth's gravity vector. Finally, none of the aforementioned classic vestibular illusions are mentioned in the Endsley and Garland book. It should be noted that the book by Endsley and Garland is well worth reading; this example is provided merely to illustrate the apparent lack of communication occurring between researchers specializing in SD and those specializing in LSA. Any number of SA or SD books could have been offered to illustrate the same point.

At times, the lack of communication between different groups leads to confusion, as was mentioned early on by Benson (1988), who noted that the advent of the concept of LSA "has led to a certain clouding of the distinction between spatial disorientation and loss of SA, of which one example is the adoption by some aircrew of the phrase 'loss of situational awareness' as a euphemism for 'spatial disorientation.' " Unfortunately, the years since 1988 have not erased the confusion between SD and LSA. This fact is exemplified by the CFIT Education and Training Aid (Flight Safety Foundation, 1996), which covers most aspects of CFIT thoroughly, but without making any discernable mention of SD. However, the CFIT Education and Training Aid lists the two basic causes of CFIT as "lack of vertical position awareness" (page 3.8) and "lack of horizontal position awareness" (page 3.8), both of which are said to involve the loss of situation awareness by the flight crew. This statement is most likely true, but fails to specify that vertical and horizontal position awareness are central to the concept of spatial orientation and its converse, SD. A more specific description of the CFIT problem would enhance the transition of SD-related knowledge to help persons at risk of CFIT.

When phrases such as LSA and CFIT are used in the aerospace literature concerning experimental research and accident investigation, care should be taken to use them in ways that will clarify the issues and avoid confusion with SD. In years past, the aerospace community came to realize that "pilot error" was not a sufficiently specific description of the cause of a plane crash. Now we must avoid the temptation to consider our job complete when we have identified some general human psychological state as the cause of an accident. As Lyons et al. (1994, page 152) have said concerning SD mishaps: "…if both an attention deficit and SD are part of the chain of events leading to an accident, each should be separately identified as a causal factor if elimination of either would have prevented the accident." This advice makes very good sense in the short term. In the long term, what is needed is to incorporate separately tabulated factors into a model that can accurately predict the amount of variance accounted for by each factor contributing to human error in flight. This requires an initial commitment to differentiate factors that usually get lumped together *a priori*.

To avoid the problem of reification, the lumping of multiple causal factors for human error under one theoretical construct name should not be attempted until sufficient data justify it. At present, SD and LSA can be defined, but many questions remain concerning each theoretical construct and the relation of the respective constructs to one another. For example, while the psychophysics of SD has been explored extensively (Guedry, 1974), there is no validated scale for assessing the experience of spatial orientation/disorientation and no formal establishment of the underlying cognitive dimensions (e.g., confirmation that visual and vestibular dimensions emerge while geographic dimensions do not). While there are scales for measuring SA, it is not clear to the authors how closely the dimensions that have emerged from existing SA scales (such as Taylor's 1990 scale) should match the three-part definition of SA (perception, comprehension, projection) as forwarded by Endsley (1988) and used to classify mishaps by Jones and Endsley (1996).

There have been a few attempts to distinguish SD from LSA as mishap contributors. Gillingham (1992) summarized 633 Class A Aircraft mishaps in the U.S. Air Force from 1980-1989 (Table 1, by permission). During this period, 356 mishaps were "operations related," 81 mishaps were classified as SD-related and 263 as LSA-related; however, there were 270 mishaps where SD and LSA were both mentioned as contributing factors. (Note that the aforementioned categories are not exclusive and hence do not add up 633, personal communication, Previc, 2002). We can infer from the earlier data of Gillingham that 43% (270 SD/LSA mishaps ÷ 633 total mishaps) of U.S. Air Force category A mishaps were SD/LSA related, while 30% [(270 SD/LSA mishaps – 81SD mishaps) ÷ 633 mishaps total] were related to LSA in the absence of SD.

Table 1. 1980-1989 USAF Class A Aircraft Mishaps – as Categorized by Safety Investigation Boards (From Gillingham, 1992, used by permission of the Journal of Vestibular Research)

	Total	Operations related	SD related	LSA related	SD/LSA related
Mishaps	633	356	81	263	270
Fatalities	795	515	115	425	437
Cost (U.S. $)	4,452M	2,558M	539M	2,012M	2,045M

Cheung and colleagues analyzed SD-related accidents (Cheung, Money, Wright, & Bateman, 1995) and LSA events (Cheung, Money, & Sarkar, 1996) in the Canadian forces. Cheung, Money, Wright, & Bateman (1995) collected 154 accident reports across category A, B, and C. They found that 14/62 (23%) of category A accidents had SD as a possible causal factor during the period 1982-1992; SD was unrecognized by the aviator in all but two of the 14 accidents, and two of the accidents appeared to be of vestibular origin (involving the somatogravic illusion). In a separate study of LSA, Cheung, Money, & Sarkar (1996) looked at class A, B, and C (U. S. Naval Flight Surgeon's Manual, 1991) accidents and incidents from 1982-1993, finding that 64 accidents were related to LSA without SD. Of these, three were category A accidents. Hence, 5% of accidents involving LSA without SD were severe enough to be classified as category A. Collectively, the data of Gillingham and of Cheung and colleagues suggest that SD and LSA are much more likely to be present together in a serious accident than is LSA in the absence of SD.

Vestibular Effects Other Than Spatial Disorientation

In addition to the aforementioned ambiguities concerning how the vestibular aspects of SD contribute to LSA and CFIT, there is a notable gap concerning how vestibular effects other than SD contribute to LSA and CFIT. The authors believe that a conceptual model of the vestibular influences upon LSA and human error should include more than vestibularly-mediated SD. Other problems associated with acceleration stimuli include extreme discomfort and distraction caused by nausea and vomiting, decrements of postural equilibrium, decrements of motor coordination, problems with visual performance, and problems with arousal, concentration, and motivation (such as occur during the sopite syndrome, first described by Graybiel & Knepton, 1976). A complete approach to the study of acceleration-induced human error should assess all these aspects of human functioning, so that the relative contribution of each aspect can be understood (Kennedy, Stanney, & Lawson, 2000).

At present, the implicit conceptual model of SD versus LSA is quite simple. If a group of concerned aerospace researchers was asked to encapsulate (via a Venn diagram) the role that vestibular acceleration stimuli play in eliciting LSA and human error, they would probably tend to distinguish acceleration-related contributors to LSA (such as the type of SD known as "the leans") from non-acceleration contributors to LSA (such as increased distraction or decreased concentration). They would also surely separate predominantly "vestibular" SD illusions from predominantly "visual SD illusions, allowing significant overlap for the fact that many cases of SD involve effects of both vestibular and visual origin. This simple conceptual model is diagrammed in Figure 1 (Note that the relative size of different circles does not reflect their relative importance).

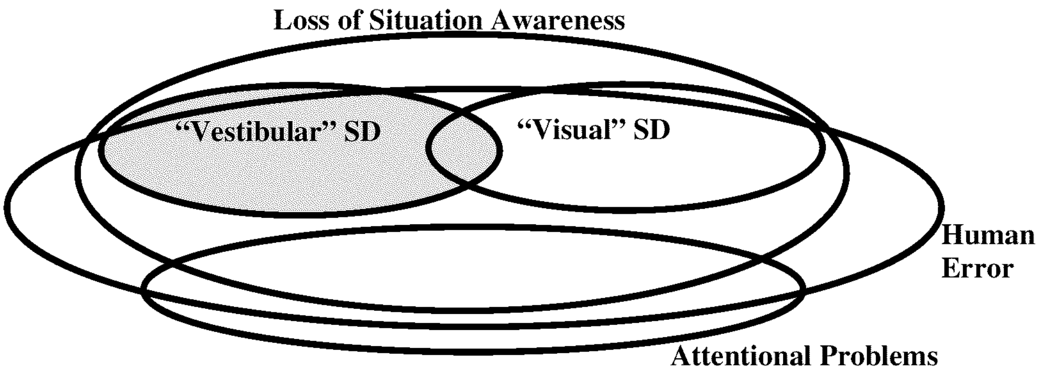

Figure 1. Two-Dimensional Venn Diagram of the Common Conception of the Role Vestibular and Visual Stimuli Play in Eliciting SD, LSA and Human Error in Flight. (Red = LSA; blue = human error, light Yellow = SD of predominantly vestibular origin.)

In Figure 1, SD can be of vestibular, visual, or combined vestibular-visual origin. SD is viewed as a subset of LSA (i.e., if one has SD, one must have a LSA, but not vice versa) and SD intersects with human error (i.e., one can have SD with or without committing an error). LSA also intersects with human error, because one can have LSA with or without committing an error. LSA intersects with attentional problems (e.g., insufficient arousal, poor concentration), but no direct link is envisioned between the vestibular stimuli and decreased attention or alertness. The simple model in Figure 1 would allow an investigator to correctly categorize "the leans" as a type of SD that fosters LSA primarily due to the misleading acceleration stimulus to the vestibular (and somesthetic) receptors, while also acknowledging that visual illusions can cause other forms of SD. However, Figure 1 leads to the conclusion that SD is the only significant means by which acceleration stimuli to the vestibular organs can disrupt human well-being and trigger LSA. This is unlikely, since acceleration stimuli to the vestibular organs probably influence attentional resources, and hence, SA (Graybiel & Knepton, 1976; Lawson & Mead, 1998). While SD is probably the most important way in which vestibular stimuli give rise to LSA and human error during flight, the authors believe it would be a mistake to conclude that

SD is the <u>only</u> way that acceleration stimuli to the vestibular organs contribute to LSA and human error. Rather, we feel that SD of vestibular origin is merely a subset of all vestibular effects that can interact with LSA and human error, as shown in Figure 2.

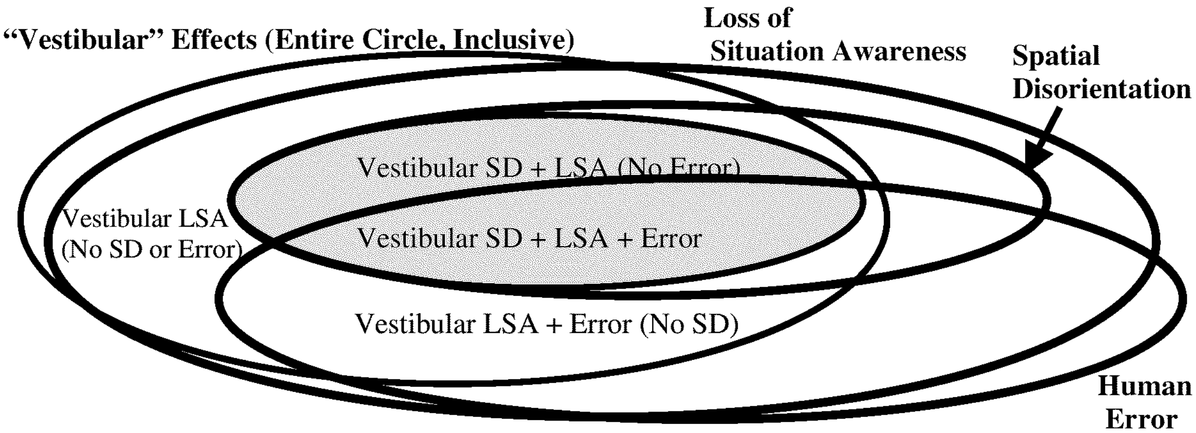

Figure 2. Two-Dimensional Venn Diagram of the Role Vestibular Stimuli Play in Eliciting LSA and Human Error in Flight. (Red = LSA; blue = human error; light yellow = SD of predominantly vestibular origin; green = vestibular effects other than SD.)

Figure 2 diagrams the possible ways that vestibular stimuli can contribute to LSA and human error. Figure 1 assumptions are preserved (in Figure 2) concerning vestibular SD as a subset of all SD and all SD as a subset of LSA. The key point for discussion is that Figure 2 hypothesizes the existence of vestibular effects other than (vestibular) SD, contributing to LSA and human error. Hettinger, Kennedy, and McCauley (1990) carried out an excellent review of the effects of motion upon human performance. They surveyed 33 studies carried out in operational and laboratory environments, noting the reported decrements of performance. Numerous motion-induced problems were noted that do not necessarily imply the presence of SD, including decrements in tests of stance, gait, postural disequilibrium, general activity level, head turning time, choice reaction time, tracing, needle threading, the spoke test (a measure of eye-hand coordination), grip strength, hand steadiness, visual tracking, critical tracking, visual acuity, single letter searching, time estimation, complex counting, mathematics, vigilance (visual and auditory), auditory monitoring, logical inference, grammatical reasoning, navigation plotting, cryptographic encoding/decoding, code substitution, and a combination lock test. Many of the aforementioned tests reflect operationally relevant aspects of in-flight SA that bear little direct relationship to the perception of one's orientation vis à vis gravity and the Earth's surface (e.g., tests reflecting general state of arousal). Other tests (e.g., of navigation or visual performance) should bear some relation both to general orientation (spatial and geographic) <u>and</u> SA, without being within the specific purview of either concept. Finally, some tests (e.g., of manual coordination) may reflect vestibular/somesthetic influences on in-flight performance that do not directly reflect SD or SA. Clearly the interactions among vestibular effects, LSA, and human error are <u>much</u> more complicated than usually implied in the literature. It is likely that the interactions among visual effects, LSA, and human error are at least as complicated. This leads to a dramatically expanded conceptualization of the role vestibular and visual effects play in LSA and human error, as diagrammed in Figure 3.

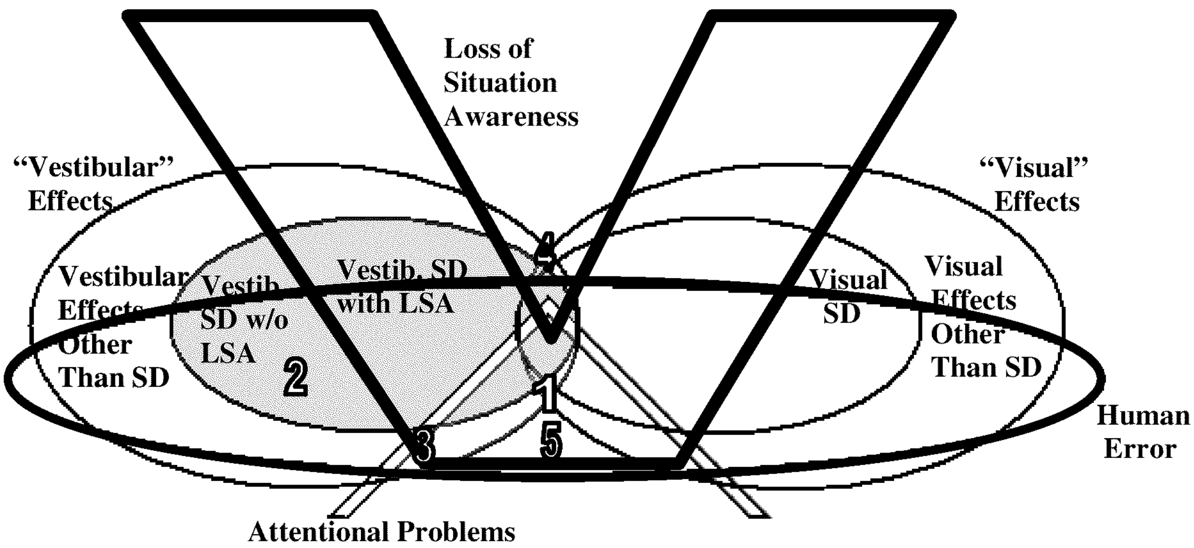

Figure 3. Two-Dimensional Venn Diagram of a More Comprehensive Conception of the Role Vestibular and Visual Stimuli Play in Eliciting LSA and Human Error in Flight. (Red = LSA; blue = human Error; green = vestibular effects other than SD; yellow = vestibular SD; numerals are explained in text.)

In this more comprehensive conception, vestibular SD is viewed as one aspect (subset) of vestibular effects and general vestibular effects can foster LSA in ways other than producing SD. Distraction and loss of concentration are viewed as problems that can arise either separately from vestibular effects or because of cognitive changes triggered by vestibular effects (including vestibular SD, motion sickness, or sopite syndrome). As denoted by numeral 1 in Figure 3, combined vestibular and visual effects can foster LSA without necessarily producing SD, by degrading dynamic visual acuity (Guedry, Lentz, & Jell, 1979). The fact that vestibular effects are a superset of vestibular SD fits the observation that certain disorienting head movements made during rotation or in high-G environments (Lackner & Graybiel, 1987) are also known to be quite sickening. Numeral 2 of Figure 3 shows that SD might be identified as a contributor to a human error (leading to a mishap) without LSA also being implicated, as one can infer (personal communication, Previc, 2002) happens in 7 of the SD-only mishaps that remain when one subtracts the 263 LSA mishaps from the 270 combined SD/LSA mishaps shown in Table 1 of Gillingham, 1992 (See Table 1 of this paper). Numeral 3 in Figure 3 represents the sopite syndrome (Graybiel & Knepton, 1976; Lawson & Mead, 1998), shown in this case as intersecting with attentional problems, LSA, and human error). Figure 3 allows for combined visual and vestibular effects to be produced without causing LSA or human error, as might occur upon changing one's glasses prescription, wherein subtle changes in one's vestibulo-ocular reflex may take place. Such benign visual-vestibular effects are denoted by numeral 4. Finally, Figure 3 allows for LSA to contribute to human error without vestibular, visual, or attentional factors being involved, as denoted by numeral 5.

Despite the fact that Venn Diagram in Figure 3 is geometrically complex, there are still numerous simplifications present. For example, the role of geographic disorientation is not depicted. Also, Figure 3 fails to acknowledge that purely cutaneous and kinesthetic mechanisms may produce LSA and human error or combine with vestibular influences. Finally, the reader should note that Figures 1, 2, and 3 represent conceptual models regarding the relative domain of different contributors to SD, LSA, and human error; the authors have not complicated these conceptual models of proximal causal factors for human error by explicitly incorporating the broad classification levels used to categorize incident and mishap outcomes. Hence, the authors have not attempted to depict how type 1 (unrecognized), type 2 (recognized), and type 3 (incapacitating) SD and type 1 (perception), type 2 (comprehension), and type 3 (projection) LSA levels fall into the models shown in Figures 1-3. Nevertheless, the reader should have no trouble guessing that type 1 (unrecognized) SD mishaps fall under "vestibular SD + LSA + Error," as shown in Figures 2 and 3. The task becomes more difficult after this point, however.

A. Vestibular Effects Other Than SD: Motion Sickness and the Sopite Syndrome

The oldest and most obvious way in which vestibular stimuli may foster decreased performance, human error, or LSA is via elicitation of the nausea syndrome. The nausea syndrome includes such signs and symptoms as nausea, retching, vomiting, cold sweating, and increased salivation. The nausea syndrome is most closely associated with travel by sea, where seasickness has created widespread operational challenges for many centuries. Pethybridge (1982) found that 70% of Royal Naval personnel are susceptible to episodes of sea-sickness (especially in rough seas or smaller ships), and that 80% of the sufferers felt they had some difficulty working on days when they felt ill (the most susceptible said they had extreme difficulty working). In the US Navy, the Naval Medical Information Management Center (1996) estimates that over 40,000 new cases of "motion intolerance" per year were recorded between 1980-92. Schwab (1943) studied 115 U.S. Naval personnel who had been hospitalized for chronic seasickness. His clinical assessment indicated that the worst-affected among these personnel were only capable of about 40% of their normal land efficiency even on large vessels, while on medium or small vessels they operated at 5-10% of their land efficiency.

Wiker and Pepper (1978) tested six U. S. Coast Guard personnel aboard a patrol boat (1978); they noticed a general decrement in six of eight performance tasks during the first steaming day. However, only three tasks (grammatical reasoning, single letter searching, and critical tracking) were degraded enough to be statistically significant for the sample obtained. Using similar tests, Wiker, Pepper, and McCauley (1980) tested three groups of six volunteers in three different Navy vessels, finding that performance on all nine measures (drawn from a battery of six tests) was significantly poorer in the patrol boat than in the other two vessels or when compared to baseline tests at the dockside. Also, motion sickness in the patrol boat overwhelmed any practice effect in performance, as was observed in the two less-sickening vessels during repeated performance testing at sea. The complex tasks were most adversely affected by motion, as were those requiring periods of sustained performance or those that allowed the subjects to control the pace of their efforts.

Some people are affected by sea travel even after returning to land; Gordon, Spitzer, Doweck, Melamed, & Shupak (1995) found that "landsickness" can strike persons of widely varying susceptibility after a sea voyage, resulting in feelings of postural instability and perceived instability of the visual field during self-movement. Similar effects have been noted following space flight (Nicogossian Huntoon, & Pool, 1989) and simulator use (Gower, Lilienthal, Kennedy, & Fowlkes, 1987). However, there is some reason to believe that postural disequilibrium aftereffects of simulator exposure may implicate disorientation mechanisms, not just those mechanisms involved in motion sickness (Kennedy, Berbaum, & Lilienthal, 1997). Moreover, postural disequilibrium is of less concern during flight operations, where the personnel directly in control of the aircraft are seated and restrained. For these reasons, postural disequilibrium will receive less emphasis in this paper.

In the aviation setting, motion sickness affects students and navigators most strongly, occasionally causing personnel to become prostrated by sickness and unable to perform their duties (Benson, 1988; Lawson, Mead, and Clark, 1997; Kay, Lawson, & Clark, 1998). Guignard and McCauley (1990) note that flying performance in rough air is generally maintained; however, they point out that additional physiological cost is required to maintain performance at pre-flight levels. The concept that additional resources must be tapped to keep performance level steady under situations of stress is a common one, having been applied to studies of fatigue and sleep deprivation (Hockey 1997; Hardy, 1999

There is little direct evidence concerning the affect of nausea on aerospace operations, but cases have been documented by Reason and Brand (1975) wherein nausea and vomiting have delayed planned American space operations (e.g., extravehicular activity) by several hours, disrupted planned work/rest duty cycles, imposed voluntary self-restrictions upon physical activity (especially head movement), and may have contributed to the early termination of a Soviet space mission. Reason and Brand (1975) described space sickness among the three crewmembers of Skylab III, noting that during the first two days of the mission, the crewmembers had to slow down their planned activities, restrict movement around the space station, and lie down to rest during the workday. A similar tendency to limit head movements was seen in Spacelab 1 astronauts (Oman, Lichtenberg, & Money, 1990), who attributed their space sickness directly to the level of physical activity demanded of them during the early part of the mission and believed they might have been able to avoid vomiting had they been allowed to delay the completion of their activities during their first days in space. Impairments of mood, feelings of increased workload, and disturbances of tracking performance were noticed (Manzey, Lorenz, & Poljakaov, 1998) during the first three weeks of a cosmonaut's stay in space, after which time his mood and performance stabilized.

The relationships among nausea, vomiting, and performance are complicated. While it is obvious that a person cannot be doing his or her job while engaged in vomiting, it does not necessarily follow that the individuals most likely to vomit will be the worst performers. Wendt and colleagues (Alexander et al., 1945; Alexander et al., 1955; Johnson & Wendt, 1964) did a series of studies using a vertical oscillation stimulus. They found that in seven of eight performance tasks, the performance of those who did not vomit was worse than those who vomited. (However, duration of exposure was not constant between the two groups.) The tasks that seemed to be most affected following exposure were mirror drawing and code substitution.

The Naval Safety Supervisor (1993) warns safety personnel that motion sickness can weaken, distract, or disorient people and that it is dangerous because is causes a loss in normal alertness and decision-making abilities, which can cause a person to make serious mistakes. Studies in various motion settings suggest that vestibular stimuli cause changes in cognitive or affective state (Lawson & Mead, 1998) that should affect SA adversely. Even mild and non-sickening vehicle motions have been associated with relaxation, drowsiness, fatigue, decreased concentration, and decreased motivation (Lawson, Kass, Muth, Sommers, & Guzy, 2001). Such effects have been collectively referred to as the sopite syndrome (Graybiel & Knepton, 1976; Lawson & Mead, 1998). For example, a senior chief petty officer in the U.S. Navy (anonymous personal communication to first author, 1998) with extensive experience at sea reported that despite being essentially immune to nausea at sea, he had often experienced overwhelming drowsiness and fatigue during the first few days of leaving harbor, whenever he had been off the ship for any extended period of time. He related an event where he was standing watch aboard ship during Desert Shield in a slow, steady sea that he found overwhelmingly sedating. He felt that in this particular case, his fitness for duty might have been compromised.

Sopite syndrome may affect some individuals profoundly. For example, a young Navy flight surgeon (anonymous personal communication to first author, 1998) related the case of an individual he knows who often finds it impossible to stay awake while riding in a car. The person often falls asleep, even while driving, and has wrecked two cars in this manner. This person does not seem to suffer from these spontaneous sleeping spells at any time when he is not in a moving situation.

Such curious experiences may be partially attributable to the motion stimulus. A large survey conducted during NATO Atlantic Fleet Operations (Colwell, 2000) asked personnel about dozens of performance problems encountered at sea. They found that the most frequently mentioned complaints were fatigue and poor sleep quality. These findings were related to ship size and sea state, being worse for small ships or increased wave motion.

According to Guignard and McCauley (1990), motion sickness can elicit lassitude, yawning, and disinclination to be active. They state that such effects which can be serious in operational situations, occasionally leading to the abandonment of performance of even critical tasks. They also point out that continuous oscillatory motions during rough seas can impair cognitive performance in a cumulative way and affect the quality of sleep and wakefulness, even among persons who are not seasick. The many factors contributing to fatigue at sea can progressively degrade and delay the work of the ship's departments, which can, in turn, reduce morale (Guignard & McCauley, 1990).

However, it is not common for motion sickness to lead to the abandonment of critical tasks. The more common outcome is that a sick person can rally and perform when the need is great enough, such as in an emergency (Reason & Brand, 1975). Birren (1949) proposed a useful distinction between peak efficiency and maintenance efficiency. He suggested that while peak efficiency (such as needed during an emergency) is likely to be unaffected by seasickness, maintenance efficiency for routine tasks may suffer during rough weather, with the crew losing interest in doing anything except the bare necessities and spending most of their free time in their bunks. Subjects in a laboratory study by Reason and Graybiel (1969) spent most of their free time in bed during a 3-day adaptation experiment within a rotating room. The onboard observer noted that even after their relatively minor initial disturbances subsided, the three subjects sought every opportunity for rest. Subjects were notably lethargic, often sleeping 12 hours or more.

There are almost no studies assessing performance during sopite syndrome. In one such study, Wright, Bose, and Stiles (1994) observed worse digit-span test performance among nauseated individuals (n=26) following helicopter flight. However, the experimenters also observed worse digit-span test performance when participants had symptoms indicative of sopite syndrome and nausea was not prominent.

Sopite syndrome may affect communication profoundly. Graybiel and Knepton (1976) noted their subjects were detached, distant, less communicative, and less willing to engage in group behavior. Such an affective state could hinder good communication, crew coordination and group SA during flight operations. Space Adaptation Syndrome has already been suggested as a factor hindering communication between ground and space crews (Kelly & Kanas, 1993).

Hettinger, Kennedy, & McCauley (1990) categorized human performance into four basic processes, using the approach of Christensen and Mills (1967, ref 17, from HKM, from Crampton). The processes were mediational, communicative, perceptual, and motor. Of these, Hettinger and colleagues noted that while good communication is required in almost all conditions where humans experience vehicle motion, this remains an aspect of motion sickness that has not received attention. This seems an area ripe for exploration, considering that communication is a vital ingredient in teamwork and the notion of team situation awareness has been discussed (Prince & Salas, 2000).

B. Vestibular Effects Other Than SD: Motion-Induced Degradation of Visual Acuity

Another important way in which certain acceleration stimuli can disrupt human performance is by making the world harder to see. Visible nystagmus (eye beating) is one of the earliest signs noted when a person is challenged by certain kinds of motion stimuli (Reason & Graybiel, 1970). Such nystagmus can degrade one's ability to interpret visual displays, which is a critical component of SA. Nystagmic responses can also be among the most persistent of aftereffects following adaptation to a motion stimulus, in some cases lasting for weeks (Guedry, 1965).

Visual acuity is commonly measured by having a stationary person read a stationary eye chart. However, visual performance is highly dependent upon one's ability to see moving objects clearly and upon one's ability to see clearly while one's head is moving through space. To view objects clearly, one must keep them steady on the retina, regardless of whether the object or the observer is moving;

this is accomplished by two eye-movement reflexes: the pursuit reflex and the vestibulo-ocular reflex. The pursuit reflex is visually mediated, using information about error of visual fixation to generate corrective eye movements that keep the visual target foveated (Stott, 1988). The vestibulo-ocular reflex uses vestibular information about head motion to generate corrective eye movements that stabilize the eyeball in space during self-movement. If the display undergoes angular oscillation about the stationary subject, the pursuit reflex will keep up with the display until approximately 1Hz display vibration frequency (Stott, 1988). However, if the subject's body is oscillated in reference to a stationary display, the vestibulo-ocular reflex will maintain gaze stability at least up to 8Hz. (Stott, 1988).

A special challenge to visual acuity occurs when an individual and a display move together through the world in a yoked fashion (Lawson, Rupert, Guedry, Grissett, & Mead, 1997), such as occurs inside a moving vehicle with internal displays. For certain combinations of acceleration and deceleration (Guedry, Lentz, Jell, 1979; Guedry, Lentz, Jell, & Norman, 1981), the vestibulo-ocular reflex will no longer be helpful in reading the head-fixed display, because it will generate eye-movements that stabilize the eye in respect to external space, but jiggle the eye in reference to the self-fixed display. For example, in the oscillation paradigm of Guedry, Lentz, and Jell (1979), the visual angle required to sustain clear visual acuity increased 2-5 times over normal. Such a dramatic visual degradation could have profound consequences for SA in flight, where critical information is obtained from visual displays.

C. Vestibular Effects Other Than SD: Fainting

A final vestibular effect of motion that is not usually discussed is fainting. Feeling faint, dizzy, or light-headed is a common reaction to unusual motions even at low G-levels (Bittner, Gore, & Hooey, 1997; Lawson, Graeber, Mead, & Muth, 2002). The physiological changes associated with fainting are sometimes seen in subjects exposed to motion experiments (Sunahara, Johnson, & Taylor, 1964; Reason & Brand, 1975; Sunahara, Farewell, Mintz, & Johnson, 1987; Sachanska, 1996; Cheung & Hofer, 2001). The authors of the present paper conjecture that only a very few people will faint outright in response to unusual motion, but for those who do, all SA has been forfeited until recovery.

Conclusions and Recommendations

It is widely known that vestibular stimuli can contribute to LSA and human error via the elicitation of SD. This paper presented evidence to warrant further exploration of the idea that vestibular effects can affect SA and human performance without necessarily triggering SD. Vestibular effects other than SD are associated with motion sickness, sopite syndrome, motion-induced loss of visual acuity, and motion-induced fainting. These various effects could potentially affect each of the three levels of SA, including perception, comprehension, and projection. Numerous examples exist of motion-related performance decrements that should be relevant to SA.

Restricting consideration solely to specific motion-related performance decrements demonstrated to be statistically significant in <u>multiple</u> studies (as reviewed by Hettinger, Kennedy, & McCauley, 1990), one can conclude conservatively that the most robust decrements following vestibular stimuli appear for tests of balance (standing and walking), critical tracking, navigation plotting, and time estimation. Of these four, only postural disequilibrium could not be called an in-flight vestibular effect that is distinct from SD. Critical tracking (Jex & Phatak, 1966), which entails manually tracking (or compensating) for a visual object that is moving unpredictably, is a psychomotor task that is clearly relevant to aviation (Blower, Albert, and Williams, 2000). The finding that navigation skills are disrupted by vestibular stimuli is very interesting, because vestibular illusions that lead to SD are considered quite distinct from geographic disorientation, or "getting lost." Yet, in Hettinger, Kennedy, and McCauley's 1990 review, we see that vestibular stimuli can disrupt certain aspects of navigation. Hence, it is conceivable that vestibular stimuli could indirectly disrupt the maintenance of good geographic disorientation.

Perhaps the strongest finding from Hettinger et al. (1990), and the one deemed by them to be least susceptible to confounding influences (such as biodynamic effects or variations in individual coping) was the observation that normal subjects perceive the passage of time less accurately while adapting to a slowly rotating room or to space flight, while subjects without a functioning vestibular labyrinth report no such effects. This is interesting, because time is an important aspect of SA (Endsley 2000). Endsley (2000) points out that individuals must constrain their limited attentional resources to the most important aspects of the situation in order to maintain SA, and that they do so partly by understanding how much time is available until some event occurs or some action must be taken. Hence, it would be interesting to determine if the known effect a vestibular stimulus can have upon temporal estimation will also be reflected by measures of SA.

The authors recommend that the relationship between aspects of SA and certain vestibular effects should be explored in the laboratory and in moving vehicles. Firstly, when a case of LSA involves a failure to perceive available cues concerning one's spatial position, the link to SD should be explored. Secondly, when a case of LSA involves a failure of attention or vigilance, the possible link to sopite syndrome should be explored. Finally, vestibular effects and LSA may intersect in cases where there people have trouble extracting needed information from head-fixed visual displays, manually tracking moving visual targets, navigating, or estimating temporal aspects of the situation. Of course, these various vestibular effects may interact with one another as well as with LSA.

Vestibular stimuli may contribute to human error in vehicle operations in ways that are seldom considered. It is not current practice for laboratory scientists who study the effects of sleep deprivation, workload, or LSA to consider their findings as potentially modified by the acceleration stimulus that occurs during most vehicle operations. Moreover, it is not current practice for scientists conducting sleep deprivation, workload, or LSA experiments inside moving vehicles to collect vehicle accelerometer data and see how it covaries with the phenomenon of interest. Since vestibular stimuli during military vehicle operations can make it more difficult to stay spatially oriented, more difficult to stay alert, more difficult to stay motivated, more difficult to read displays, more difficult to coordinate manual activity, more difficult to track targets, and more difficult to estimate time, then the authors conjecture that the acceleration stimulus to the subject is not merely a concern for spatial orientation researchers, but for all researchers interested in human performance during vehicle operations.

The current approach views human error in aviation as a phenomenon that is partially mediated by vestibular mechanisms, via the production of SD. However, the current approach treats all other vestibular effects of motion as independent of human error in aviation. Instead, we should widen our scope of assessment to include more than one or two dependent measures at a time; we should measure SD, LSA, motion sickness, sopite syndrome, postural disequilibrium, manual dexterity, visual acuity and time estimation together when feasible, so a true understanding can be gained of the relative contribution of each to a human's performance outcomes (Kennedy, Stanney, & Lawson (2000).

If the concepts encompassed by the phrases SD and LSA are to coexist meaningfully and be applied appropriately in the future, much work will be necessary to confirm that they represent necessary and consistent constructs, to determine their dimensions, and to understand their points of convergence and divergence. Without such basic research, our attempts to understand the mental state that contributes to most accidents will be confused by ill-characterized concepts whose relations are unknown.

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